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Simplified Grasping and Manipulation with Dextrous Robot Hands

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ABSTRACT

A method is presented for stably grasping 2 dimensional polygonal objects with a dextrous hand when object models are not available. Basic constraints on object vertex angles are found for feasible grasping with two fingers. Local tactile information can be used to determine the finger motion that will reach feasible grasping locations.

With an appropriate choice of finger stiffnesses, a hand can automatically grasp these objects with two fingers. The bounded slip of a part in a hand is shown to be valuable for adapting the fingers and object to a stable situation. Examples are given to show the ability of this grasping method to accommodate disturbance forces and to perform simple part reorientations and regrasping operations.

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1.0 INTRODUCTION

Most current robot hands do not have the dexterity that is required for many assembly operations. To meet this need, multi-fingered hands with individually articulated joints have been developed [Hanafusa and Asada, 1977], [Salisbury, 1982], and [Okada, 1982]. These hands have from 3 to 11 degrees of freedom (DOF) and present some interesting problems for control, sensing and cooperation among fingers [Hollerbach, 1982].

In this paper, finger level requirements will be defined to grasp objects, prevent them from slipping from a grasp, and to perform some simple reorientations and regrasps of parts within a dextrous hand. These finger level requirements include tactile sensing as well as position, force, and stiffness control. The problems of servo level hand control issues and the specifics of hand mechanisms have been considered by [Salisbury and Craig, 1982].

Previous studies of dexterous robot hands have assumed knowledge of object shape, location, and orientation. This information was used to determine optimum grasp points, [Hanafusa and Asada, 1977] and necessary forces for static equilibrium, [Salisbury, 1982]. When this knowledge is unavailable, it is useful to develop grasping strategies that rely on local tactile feedback, object shape constraints, and friction forces to ensure viable grasps.

We consider objects that can be modelled as the volume generated by a constant size polygon translated normal to its plane. If these objects are restricted to lie on a supporting plane, the problem is reduced to planar motion and forces, with only three degrees of freedom of motion instead of six. Many grasping problems, such as acquiring a part that is resting on a table, have a two dimensional nature to them. Since gravity is normal to the support surface, its only contribution is the frictional force between the part and the surface until the part is removed from the surface.

The finger-object contact is modelled as a simple point contact with friction. With this assumption, a finger can apply normal and tangential forces to the object, but no moments. The point contact simplifies rolling about a finger, because the rotation center is fixed.

2.0 STABLE GRASP DEFINITION

There are three necessary conditions for a stable grasp. The object must be in equilibrium; there is no net force or moment

$$\sum_i \vec{F}_i = 0 \tag{1}$$

$$\sum_i \vec{r}_i \times \vec{F}_i = 0 \tag{2}$$

where $\vec{F}_i$ are the i force vectors and $\vec{r}_i$ are the distance vectors from one point to each finger.

All forces must be within the "cone of friction" as in Fig. 1 so that there is no slip at the fingers:

$$\mu\, F_N > |F_t| \qquad \text{or} \qquad |\alpha| < \tan^{-1}\mu = \phi_s \tag{3}$$

where F_N is the force component normal to the surface, F_t is the tangential component, μ is the coefficient of friction, ϕ_s is the angle of friction, and α is the angle of force with respect to the surface normal.

The final condition for stability is that it should be possible to increase the magnitude of the grasping force to prevent any displacement due to an arbitrary applied force. To restrain a rigid planar body from motion, four frictionless point contacts are required [Lakshminarayana, 1978]. Since a point contact with friction can apply forces in more than one direction, only two fingers with friction are necessary. When an applied force is larger than the friction forces, it is necessary to increase the normal force at each finger to prevent object displacement.

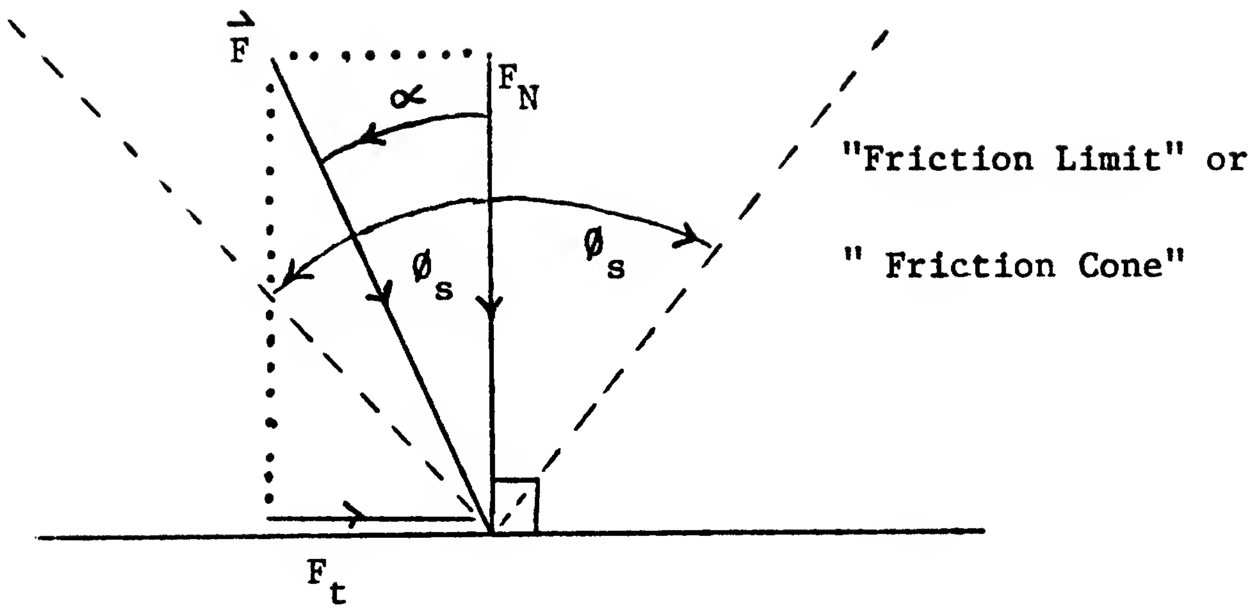


Figure 1. Friction Principles

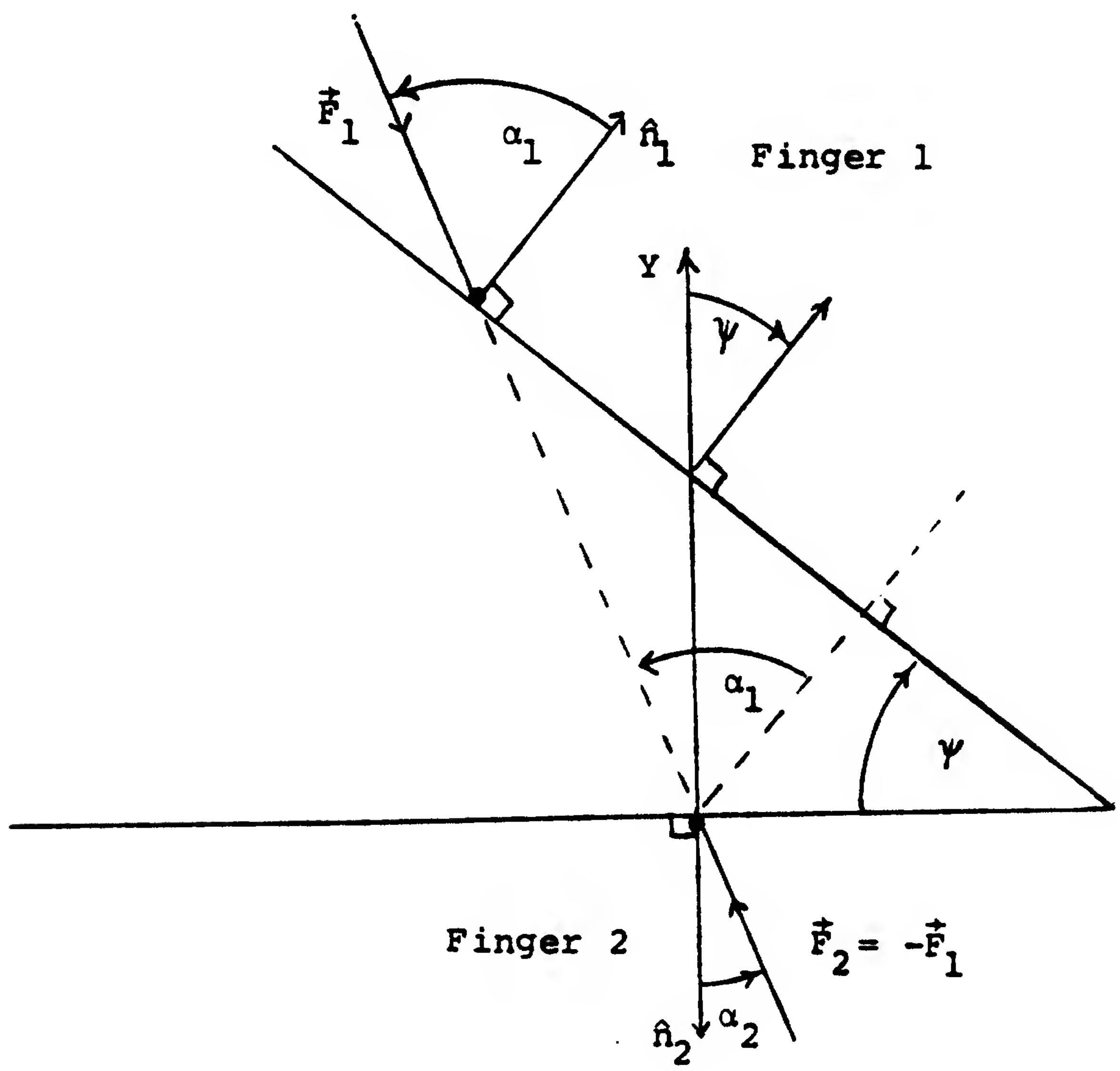


Figure 2. Angles of Forces for Polygon in Equilibrium

3.0 GRASPABILITY

Consider the portion of a polygon grasped by two fingers as in Fig. 2, where the angles are defined as in Fig. 1. To prevent the fingers from sliding, the force angles must be within the friction cone. So we must satisfy:

$$\phi_s > \alpha_1 > -\phi_s \qquad \text{and} \qquad \phi_s > \alpha_2 > -\phi_s \tag{4}$$

where the two force angles are measured in the counter clockwise sense from the surface normals.

For equilibrium, the two forces must be colinear, of equal magnitude, and opposite sign to satisfy (1) and (2). So for a polygon, the two force angles can not be independent, and are related by:

$$\alpha_2 = \alpha_1 + \psi \tag{5}$$

where ψ is the angle between the surface normals measured from the normal at the second finger to the normal at the first finger.

Thus for a stable grasp,

$$|\psi| < 2|\phi_s| \tag{6}$$

The closer the sides are to parallel, the smaller the coefficient of friction required to grasp them stably.

4.0 FOUR PHASES OF STABLE GRASP

Fig. 3 shows four phases to find, grasp, and pick up a part. These are the approach phase, the initial touch phase, the initial grab phase, and finally, the stable grasp.

Approaching an object to be grasped is simple, but time-consuming if a small part is anywhere on a large surface. Without vision, an object's location and orientation may be unknown, but can be found using a sense of touch. Object shape and size will influence the finger positions that minimize contact time.

When one finger contacts the part (initial touch phase), much uncertainty about the part's location has been removed. But as Fig. 4 shows, local contact information from an object does not determine its orientation. If the object moves when touched, multiple contacts can detect the direction of motion of the part. Mason [1982] has analyzed the motion of objects on a frictional surface and has shown that the rotation center can be predicted from the contact type at a pushing constraint (a finger). The rotation center indicates where the bulk of the object is so that the other finger can successfully grab it. During the approach and initial touch phases, it is important to have low finger stiffness and velocity to prevent parts from flying away from the finger impact.

When the two fingers have successfully intercepted the object, the initial grab phase, the finger positions and forces are adjusted to get to a stable grasp. During this phase, the object may translate and rotate while the fingers are positioned, even breaking contact with both fingers. A method to achieve the stable grasp is described in Sect. 6.0.

Since the complete object boundary is not known, and probably only the two local regions around each finger, this stable grasp is not necessarily optimal in the sense of having greatest resistance to disturbing forces. Other finger locations might give more robust grasps.

In the stable grasp phase, the final position of the part in the hand is still uncertain, but it is in a stable orientation and location. This position is sufficient for it to be picked up. For operations requiring precise parts positioning, the object may need to be regrasped in known locations. That problem would require recognizing the part and its orientation, and complete object models.

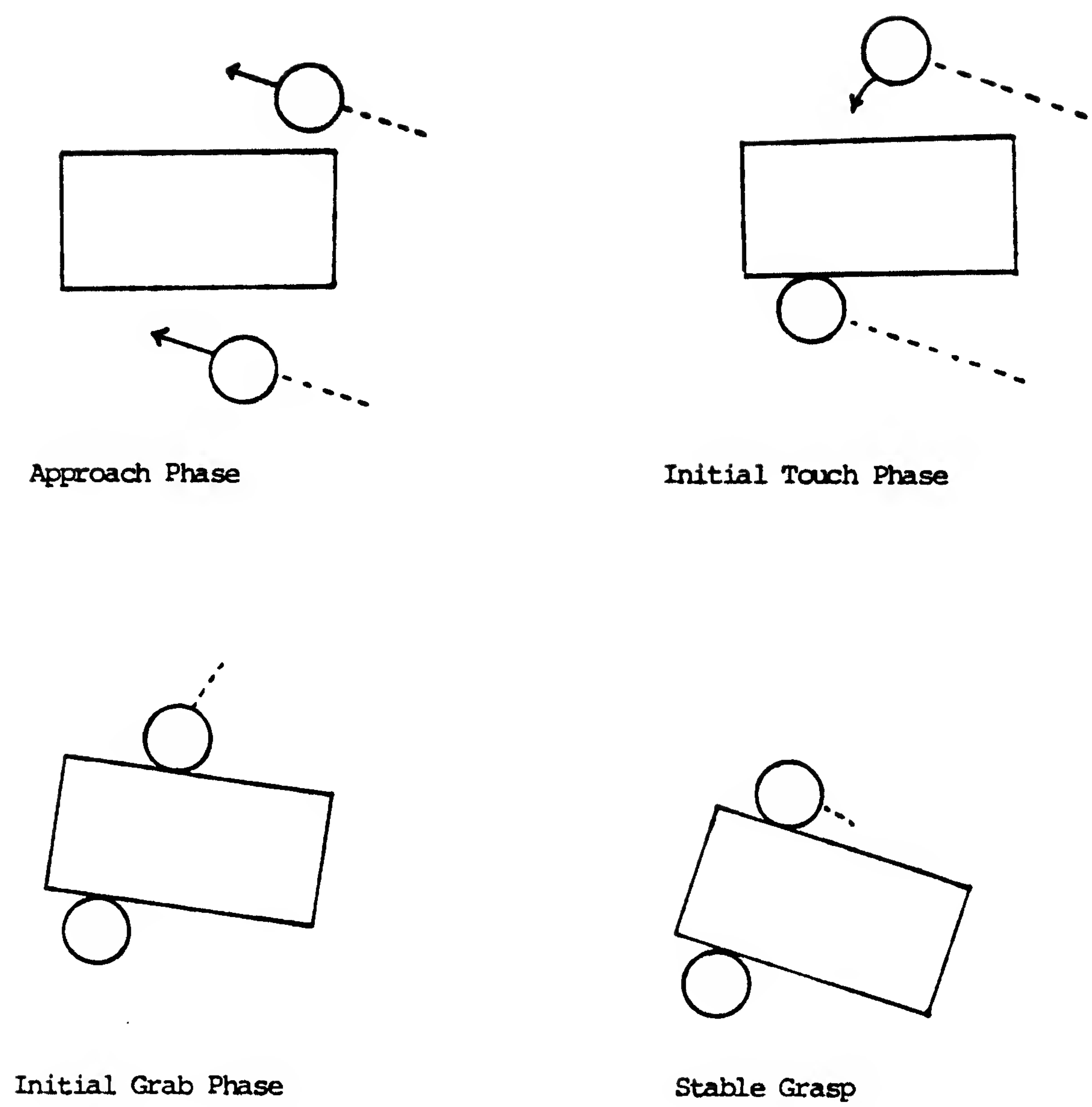


Figure 3. Phases of 2 Finger Stable Grasping

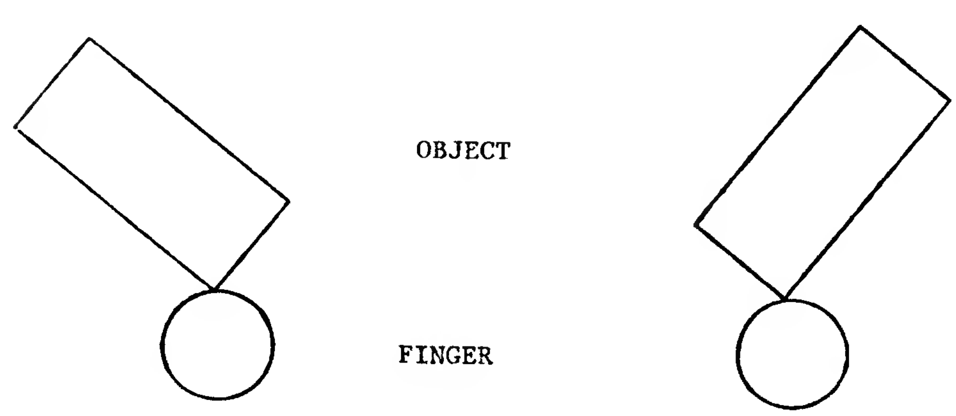


Figure 4. Object Uncertainty with Local Contact

5.0 TACTILE FEEDBACK FOR STABLE GRASPS

There are at least two categories of tactile sensing for grasping. The simpler requires determining the direction of surface normals or distinguishing between vertexes and sides, but more complicated grasping tasks may require sensing the angle of force with respect to the surface normal to prevent slip or to keep the tangential compliance high. As shown in Sect. 3.0, for polygonal objects there are limits on the surface normal range for a stable grasp with 2 fingers. By sensing the surface normals at two fingers, it is possible to determine if the attempted finger closure will result in a stable grasp.

Fig. 5 shows a simple method of determining the surface normal using a relatively rigid finger with circular cross section. Since a circle and a line are tangent at one point, with the radius perpendicular to the tangency, the location of the contact on the circumference of the finger gives the normal vector at that point. This method is independent of the applied forces at the finger.

If the surface normals are out of the capture range for stable grasping, one or both fingers should be moved to a more favorable location. For a two dimensional object with a smooth closed contour, there are always at least two pairs of colinear but oppositely directed surface normals [Jameson, 1984 and Kuiper, 1964], which will be graspable even for very small coefficients of friction. One grasp pair is the two points on the contour with the maximum linear distance between them.

It may be necessary to find a vertex to be able to stably grasp some polygonal shapes. A vertex contacting a compliant surface has a larger effective friction cone [Fearing, 1983]. If the angle between the two surface normals is unacceptable, the fingers should be moved away from the included angle. This will ensure finding a vertex or perhaps more graspable surface normals.

The most reliable strategy for finding better grasp points requires sliding the finger along the object perimeter until favorable conditions are met. A quicker method might move one finger without touching to a region where it is assumed the object is located. But guessing where to move the second finger can result in an unstable position, without knowledge of object shape and orientation.

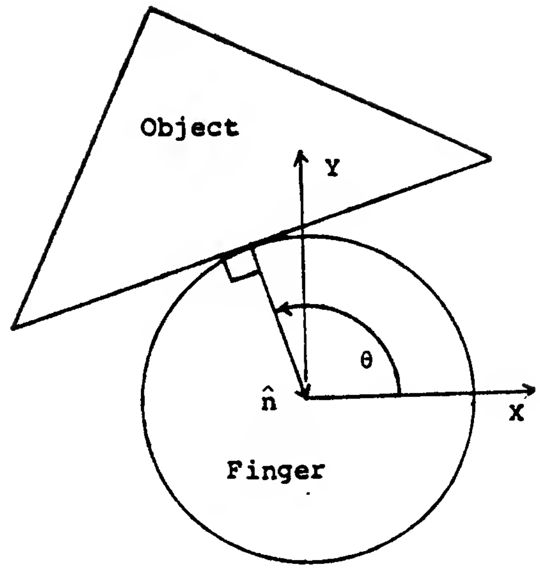
6.0 HAND PRIORITY GRASP

In the general initial grab, the hand and the object will move during the grasping operation. Object priority grasping, where the fingers slide to stable grasp positions, and the object remains fixed is described in [Fearing, 1983]. In this section, it is assumed that the finger forces are much larger than the inertia of the object and the frictional forces between the object and its support surface. If the instantaneous net force on the object is approximately zero, the quasistatic assumption can be used. This will be used to avoid considering the dynamics of the problem.

We look at a method that uses slip at the fingers and object motion to adapt the object to the hand in a stable grasp. This will be referred to as the "hand priority grasp". We would like to show how uncertainty can be reduced sufficiently to ensure a stable grasp, without knowing the precise object pose. If the object moves when the hand tries to grasp it, how can it be ensured that the object will move to a stable position instead of slipping out of the hand?

Mason [1982] was able to predict the behavior of planar objects on a plane being pushed and choose a series of pushing paths to eliminate uncertainty in position of a part, regardless of its original location. By adapting the flavor of that analysis to two fingers, the motion of the grasped object can be qualitatively described. A simplification will be to ignore the time dependence (velocities), and just consider the final position and orientation.

There are three classes of motion of interest for the initial grab phase. They are: sliding contacts at both fingers, rolling contacts at both fingers, and a sliding contact at one finger with rolling at the other. If the two finger forces are within the friction cones, there will be rolling contacts at both fingers if the forces are not colinear.



$\hat{n} = -\hat{x}\cos\theta - \hat{y}\sin\theta$

Figure 5. Determining the Surface Normal

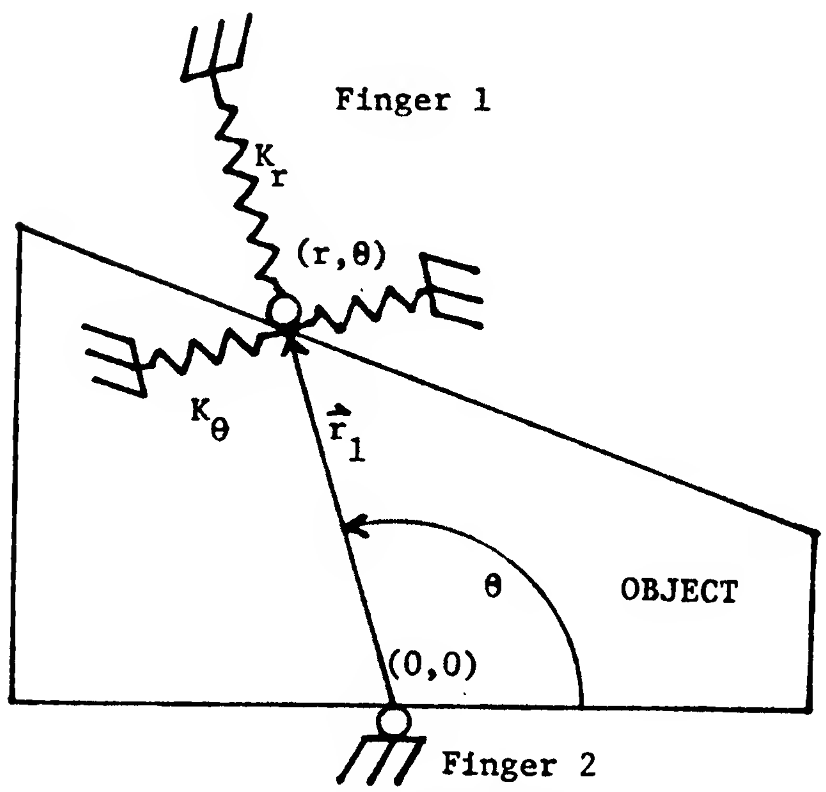


Figure 6. Polar Stiffness Representation

Assume that both fingers are already in contact with the object, with a sliding contact at finger one, and a rolling contact at finger two because the angle of force is within the friction cone there. Finger two is used as a fixed position constraint that provides a reaction force, and is the origin of the coordinate system. Both fingers will be considered to have a negligible radius so that an object rolling at a finger will have a constant rotation center.

Assume that finger one has a controllable stiffness that can be set to ensure a stable grasp. We start with the polar stiffness representation of the finger force at finger one:

$$\vec{F}_1 = \begin{bmatrix} F_r \\ F_\theta \end{bmatrix} = \begin{bmatrix} F_{ro} \\ F_{\theta o} \end{bmatrix} + \begin{bmatrix} k_{rr} & k_{r\theta} \\ k_{\theta r} & k_{\theta\theta} \end{bmatrix} \begin{bmatrix} \Delta r \\ \Delta\theta \end{bmatrix} \tag{7}$$

Since slip may occur at any finger, in combination with object rotation, the problem is simplified by restricting the finger motion to a straight line. A good straight line to choose is the line between the two fingers, (motion only in the radial direction, $\Delta\theta \rightarrow 0$). With the line of force along the line of motion of finger one, the fingers will end up in a stable grasp position. This can be achieved by: $k_{\theta\theta} \rightarrow \infty$, $k_{r\theta}, k_{\theta r} \rightarrow 0$ and $F_{\theta o} \rightarrow 0$. So

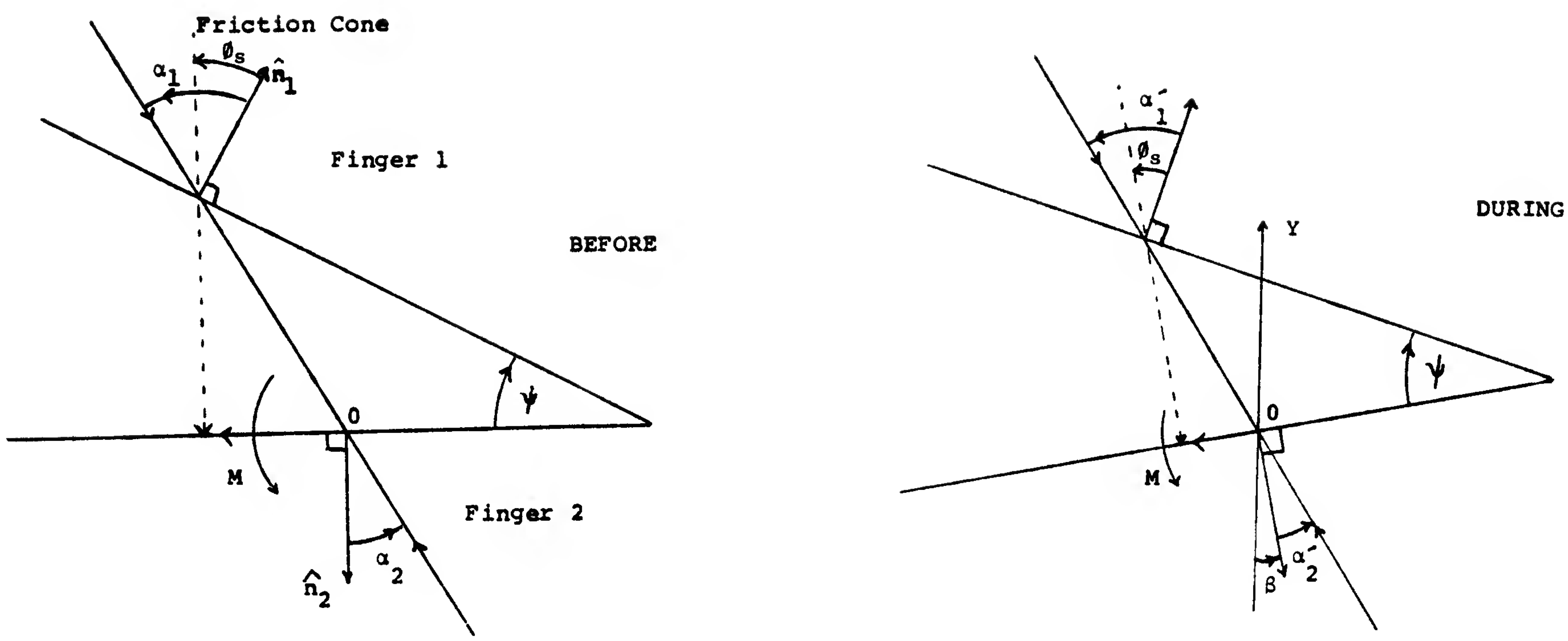


Figure 7. Hand Priority Grasp

$$\vec{F}_1 = \begin{bmatrix} F_r \\ F_\theta \end{bmatrix} = \begin{bmatrix} F_{ro} + k_r \Delta r \\ k_\theta \Delta \theta \end{bmatrix} \tag{8}$$

In a practical mechanism, the displacement perpendicular to r would be non-zero. However, this analysis should approach that case when the radial stiffness is much smaller than the stiffness perpendicular to it. A model of this stiffness representation is presented in Fig. 6. This is very similar to the structure used by Hanafusa and Asada [1977], although the tangential stiffness did not enter that model.

Fig. 7 shows an initial grasp that satisfies the assumption of a sliding contact at finger one, and a fixed or rolling contact at finger two. Even though the applied forces are colinear, there may still be a rotation about finger two because the sliding finger has a force that acts at the friction angle, and this gives a moment about finger two.

As the object rotates about finger two, the fingers stay along the same line, but the surface normals change with respect to the applied force. So the force angles after a rotation are:

$$\alpha_1' = \alpha_1 - \beta \quad \text{and} \quad \alpha_2' = \alpha_2 - \beta \tag{9}$$

where β is the rotation angle of $\hat{n}_2$, as measured from the -y axis.

Fig. 8 graphically describes the behavior of the force angles. The figure shows the initial conditions of finger one outside the friction limit, and finger two within. Rotation occurs in the positive (counterclockwise sense) until the force at finger one gets within the friction cone. At that point, the forces are colinear, the moment about finger two is zero, and the object is stably grasped.

Fig. 8 also explains the limit on vertex angles of Sect. 3.0. Consider an object with the angle between surface normals greater than the width of the friction cone, but with the reaction force at finger two within the friction cone as in Fig. 9. Now as the object rotates around finger two, the force at finger two will reach the friction limit before the force at finger one does. When this happens, with both fingers sliding in the same direction, the object will slip from the grip.

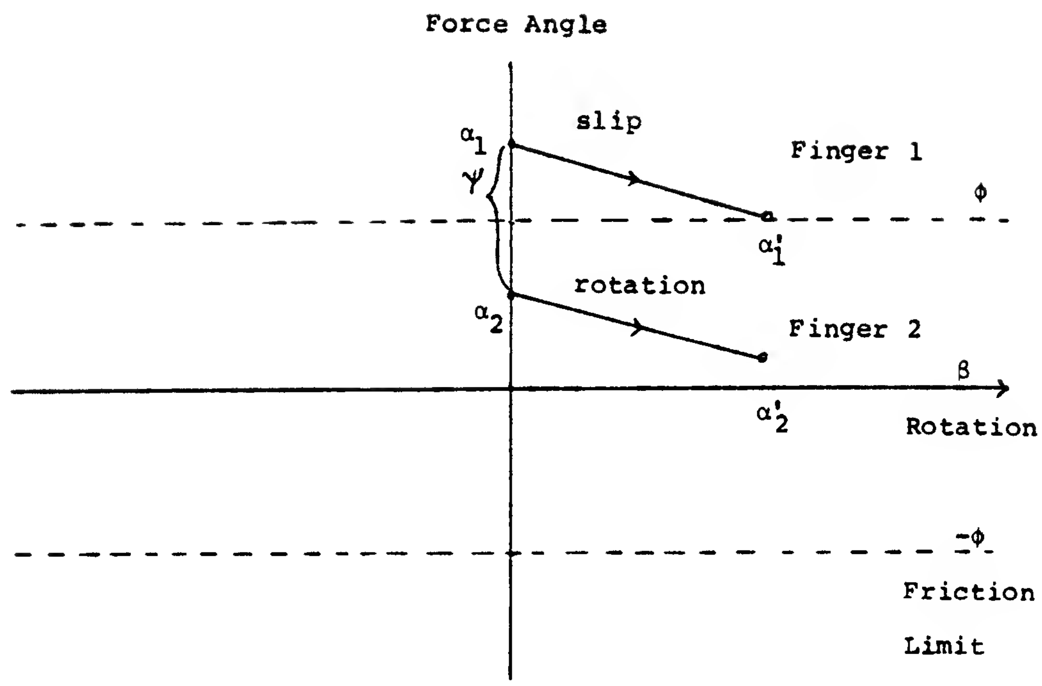


Figure 8. Rotation During Hand Priority Grasp

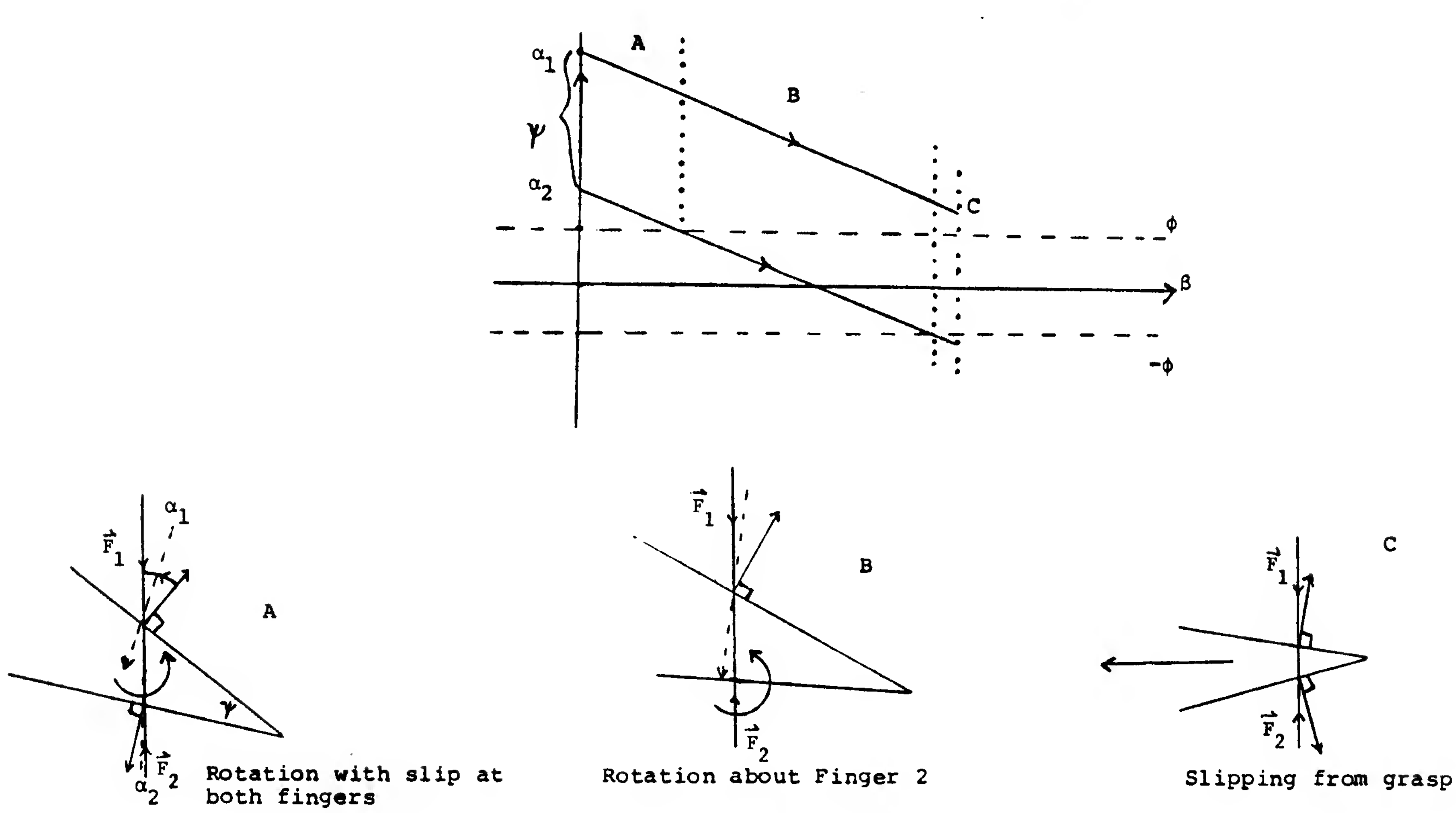


Figure 9. Ungraspable Object

If slip occurs at both fingers, but the vertex angle is within the limit set by the friction, a stable grasp will still be achieved. For example, if both finger force angles are greater than the positive friction limit, there will be a positive moment due to each finger force, and rotation will occur counterclockwise, with a rotation center somewhere between the two fingers. Now as soon as one finger force gets within the friction cone, rotation will occur about that finger, and then the analysis is the same as previously. It should be noted that when both fingers are slipping during the initial grasp phase, there will be some translation of the object.

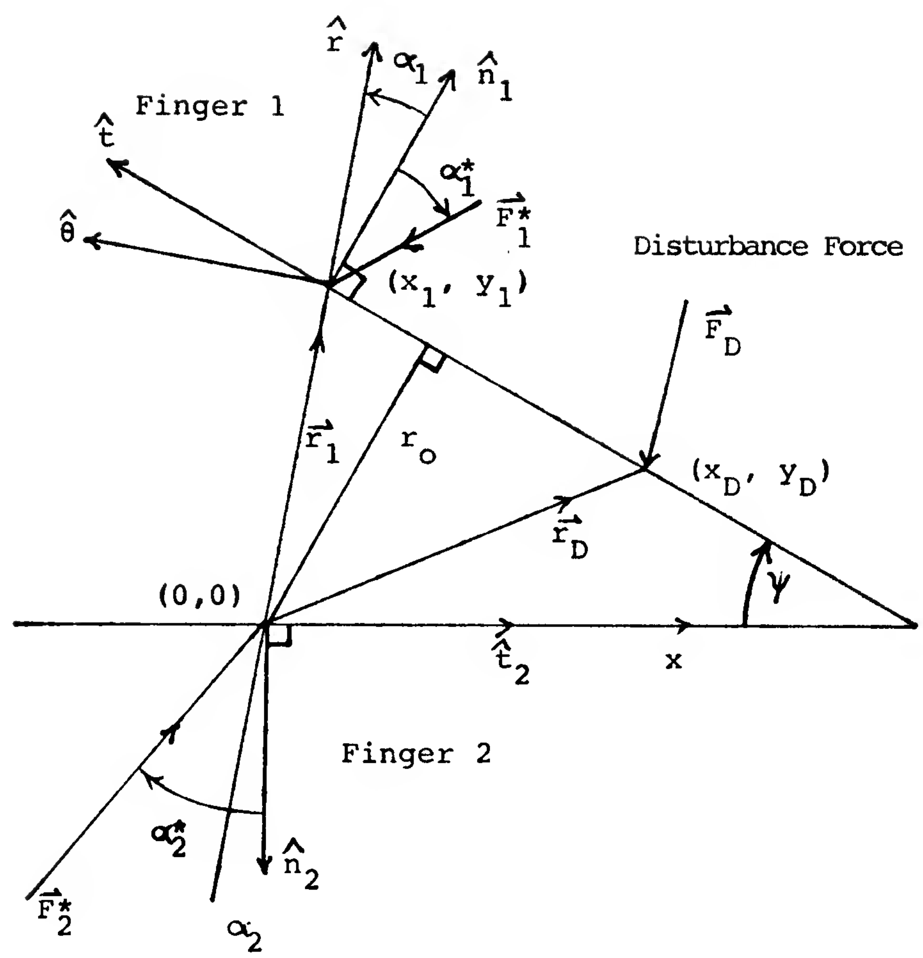


Figure 10. Grasping with Disturbance Forces

There is a hysteresis band in the stable region between the two friction limits. Any displacement that leaves the force angles inside this band will not generate a restoring force. But a displacement that moves the force angles outside this hysteresis band will generate a restoring force that tends to get both angles within stable limits again. Because of this hysteresis band, the orientation of the object is uncertain when it is stably grasped without some sensing of surface normals.

7.0 DISTURBANCE FORCES

One way to evaluate the stability of the "hand priority" grasp is by determining behavior when a disturbance force is added. The object is no longer completely restrained, but if the motion is bounded, (the object does not slip out of the hand), it can be thought of as stably grasped when motion has stopped. If the angles of the reaction forces are within the cone of friction, the grasp will be stable. This disturbance force is considered to act through a fixed point on the object. An example of this is a gravitational force acting through the center of gravity.

The assumptions are the same as for Sect. 6.0, with finger two a fixed point contact with friction that provides a reaction force, and finger one a point contact with friction where the tangential force is due to the reaction there. F_{ro} is a known constant. The system of forces would be statically indeterminate without these assumptions.

For convenience the finger force and the disturbing force are defined in two coordinate systems:

$$
\begin{aligned}
\vec{F}_1{}^* &= F_{ro}\,\hat{r} + F_\theta\,\hat{\theta} \\
\vec{F}_D &= F_{Dx}\,\hat{x} + F_{Dy}\,\hat{y}
\end{aligned}
\qquad (10)
$$

where $\vec{F}_D$ is the disturbing force applied at (x_d, y_d), and the $*$ distinguishes this force from the force at finger one with no disturbance. This situation is shown in Fig. 10.

At finger two, equilibrium requires:

$$\vec{F}_2^{\,*} = -(\vec{F}_1^{\,*} + \vec{F}_D) \tag{11}$$

For moment balance at finger two:

$$\vec{r}_1 \times \vec{F}_1^{\,*} + \vec{r}_D \times \vec{F}_D = 0 \tag{12}$$

Define

$$M_D = (\vec{r}_D \times \vec{F}_D) \cdot \hat{z} \tag{13}$$

where M_D is the moment due to the disturbance.

Since the distance between the two fingers changes with the rotation, the finger one position vector is given by the geometry shown in Fig. 10 as:

$$\vec{r}_1 = \begin{bmatrix} x_1 \\ y_1 \end{bmatrix} = \frac{r_o}{\cos(\alpha_1-\beta)} \begin{bmatrix} -\sin(\alpha_1+\psi) \\ \cos(\alpha_1+\psi) \end{bmatrix} = \frac{r_o\ \hat{r}}{\cos(\alpha_1-\beta)} \tag{14}$$

where r_o is the normal distance from finger two to the opposite side, and β is the rotation angle as it was defined in Fig. 7. The moment due to the reaction force at finger one is:

$$\vec{r}_1 \times \vec{F}_1 = |\vec{r}_1|\, F_\theta\, \hat{z} \tag{15}$$

For moment balance:

$$-M_D = \frac{r_o F_\theta}{\cos(\alpha_1-\beta)} \tag{16}$$

Since the moment due to the disturbing force is known, equation (16) can be solved for the necessary tangential reaction force at finger one:

$$F_\theta = \frac{-M_D \cos(\alpha_1-\beta)}{r_o} \tag{17}$$

To find the normal and tangential components of the force at finger one, the force vector is rotated by $\alpha_1' = \alpha_1-\beta$, which is the angle from $\hat{n}_1$ to $\hat{r}$:

$$\begin{bmatrix} F_{1t}^{*} \\ F_{1N}^{*} \end{bmatrix} = \begin{bmatrix} \sin\alpha_1' & \cos\alpha_1' \\ \cos\alpha_1' & -\sin\alpha_1' \end{bmatrix} \begin{bmatrix} F_{ro} \\ F_\theta \end{bmatrix} \tag{18}$$

to get the ratio of tangential to normal force at finger one:

$$\frac{F_{1t}^{*}}{F_{1N}^{*}} = \frac{F_{ro}\ ro\ \sin(\alpha_1-\beta) - M_D\ \cos^2(\alpha_1-\beta)}{r_o F_{ro} \cos(\alpha_1-\beta) + M_D \sin(\alpha_1-\beta)\cos(\alpha_1-\beta)} \tag{19}$$

Now for equilibrium at finger 2:

$$\begin{aligned} F_{2x}^{*} &= -F_{1x}^{*} - F_{Dx} \\ F_{2y}^{*} &= -F_{1y}^{*} - F_{Dy} \end{aligned} \tag{20}$$

Rotating the force vectors at finger one:

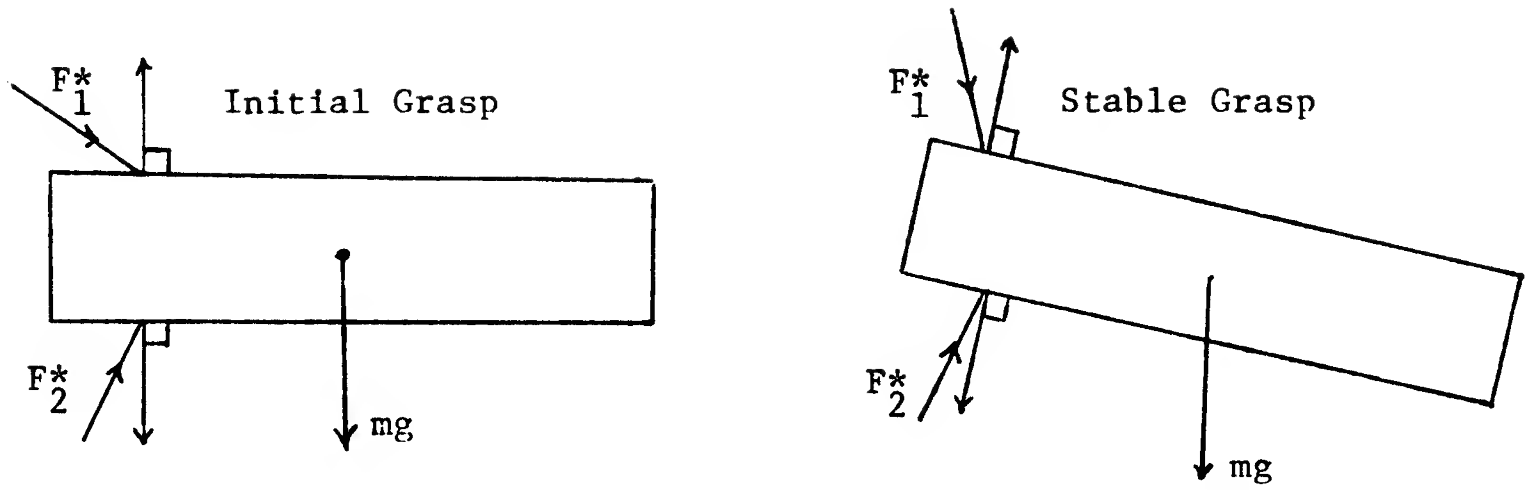


Figure 11. Grasping with Gravitational Force

$$\begin{bmatrix} F^*_{2x} \\ F^*_{2y} \end{bmatrix} = - \begin{bmatrix} F_{Dx} \\ F_{Dy} \end{bmatrix} + \begin{bmatrix} \sin(\alpha_1+\psi) & \cos(\alpha_1+\psi) \\ -\cos(\alpha_1+\psi) & \sin(\alpha_1+\psi) \end{bmatrix} \begin{bmatrix} F_{ro} \\ F_\phi \end{bmatrix} \tag{21}$$

And rotating to get tangential and normal components at finger two:

$$\begin{bmatrix} F^*_{2t} \\ F^*_{2N} \end{bmatrix} = \begin{bmatrix} \cos\beta & \sin\beta \\ \sin\beta & -\cos\beta \end{bmatrix} \begin{bmatrix} F^*_{2x} \\ F^*_{2y} \end{bmatrix} \tag{22}$$

Thus the ratio of tangential to normal force at finger two is:

$$\frac{F^*_{2t}}{F^*_{2N}} = \tag{23}$$

$$\frac{-F_{Dx}\cos(\beta) - F_{Dy}\sin(\beta) + F_{ro}\left[\sin(\alpha_1+\psi-\beta) - \dfrac{M_D}{F_{ro}\, r_o}\cos(\alpha_1-\beta)\cos(\alpha_1+\psi-\beta)\right]}{F_{Dy}\cos(\beta) - F_{Dx}\sin(\beta) + F_{ro}\left[\cos(\alpha_1+\psi-\beta) + \dfrac{M_D}{F_{ro}\, r_o}\cos(\alpha_1-\beta)\sin(\alpha_1+\psi-\beta)\right]}$$

The reaction forces at the two fingers necessary for equilibrium have angles with respect to the surface normals defined as:

$$\alpha_1^* = \tan^{-1}\frac{F^*_{1t}}{F^*_{1N}} \quad \text{and} \quad \alpha_2^* = \tan^{-1}\frac{F^*_{2t}}{F^*_{2N}} \tag{24}$$

Equations (19) and (23) can be used to predict the behavior of a grasped object for any type of disturbance force. It is convenient to use the graphical method presented previously to determine rotation directions, unstable conditions, and degree of stability. Examples will be given for two types of disturbance forces–a gravitation force, and a force due to a third finger.

Consider an object held perpendicular to gravity (so that forces are in a plane). The weight acts through the center of gravity in the $-y$ direction as in Fig. 11 so

$$F_{Dy} = -mg \qquad F_{Dx} = 0 \tag{25}$$

Now when the object rotates, the position vector to the disturbance force maintains a constant distance, but changes direction, so the net disturbance moment will decrease. The position vector

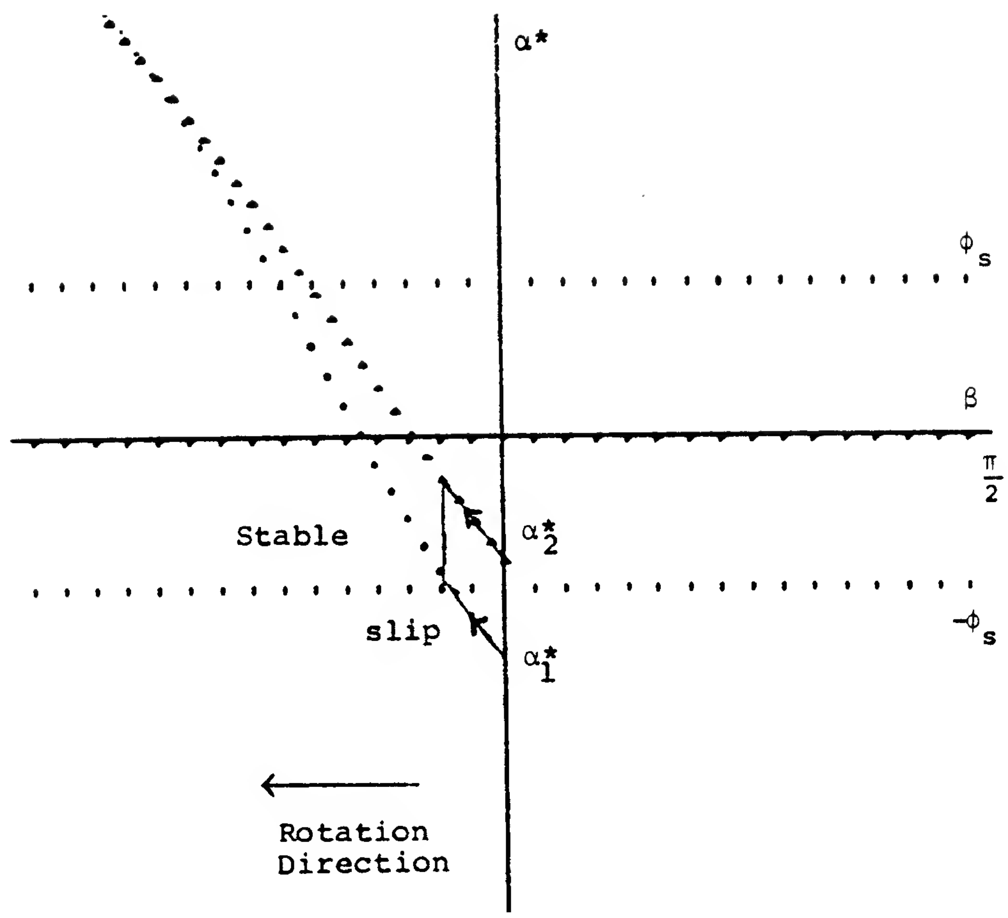


Figure 12. Rotation Due to Gravity

and disturbance moment are given by:

$$\vec{r}_D = r_D \begin{bmatrix} -\sin(\theta_D + \beta) \\ \cos(\theta_D + \beta) \end{bmatrix}$$

$$M_D = | \vec{r}_D \times \vec{F}_D | \qquad (26)$$

where θ_D is the angle between $\hat{y}$ and $\vec{r}_D$.

The behavior of the object in Fig. 11 is shown by the graph in Fig. 12. The object rotates about finger two in the clockwise sense, and slips at finger one. After a small rotation, the object ends up in a stable grasp. The amount of rotation can be reduced by increasing the radial force, or by making $k_r > 0$.

The disturbing force can also be used to bring finger force angles back within the cone of friction. Fig. 13 shows how a third finger can be used to grasp an object that can't be grasped with just two fingers. It is important to note that this third force can be applied with a wide range of locations, directions, and magnitudes. It is only critical if all slip must be prevented.

8.0 SIMPLE MANIPULATIONS

If the third finger controls the amount of rotation, manipulation is possible. This method can be extended to the "baton twirling" problem shown in Fig. 14. The object is held in a two finger stable grasp in Fig. 14A. A third finger applies a disturbance force directed towards finger two (Fig. 14B). This causes the object to rotate about finger two in the clockwise direction. Finger one can now be removed, and the object will again rotate clockwise into a new stable configuration, grasped between fingers two and three. The process can be repeated indefinitely if rotation without slip about the fixed finger is ensured.

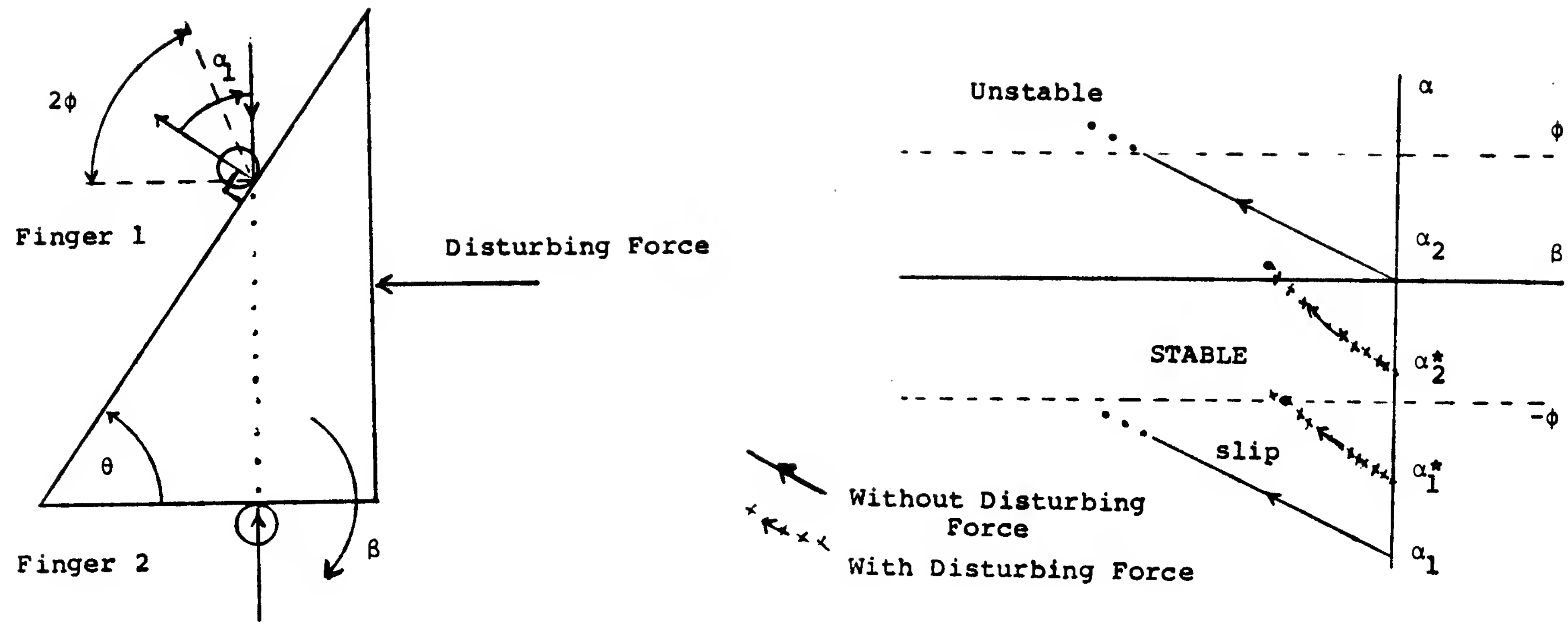


Figure 13. Making a Grasp Stable

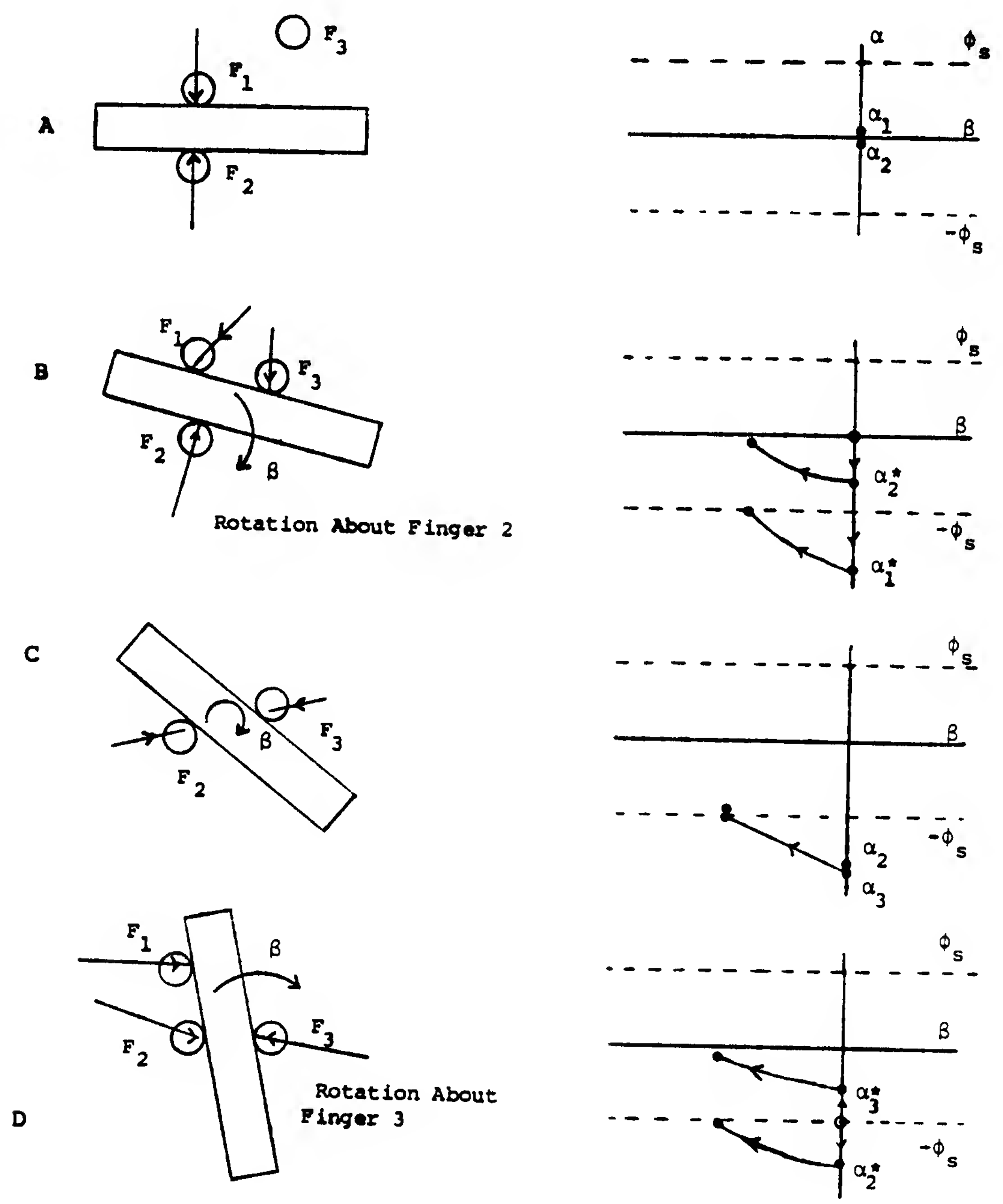


Figure 14. "Classical" Reorientation/Regrasp Example

Another simple manipulation is rolling a part between two fingers. One method to do this is to determine the trajectory in space for a contacting finger such that it causes the finger and part to roll along each other [Okada, 1982]. This has the disadvantage that the locations of the fingers and the part, and the dimensions of the part must be known accurately beforehand.

With our method, all that is necessary is to add a disturbance force (F_θ) at finger one. The object will now have a net moment about finger 2, so that it will rotate. However, slip at finger one, determined by the friction cone, limits the maximum moment that can be applied. This slip could be a problem in some applications where the location of the part is crucial. An accurate friction model and perhaps the moment of inertia of the grasped object are needed to predict the position without tactile feedback from the fingers.

If in equation (7), we define $\Delta\theta = \theta_o - \theta$, where θ is the actual angle, then the nominal position θ_o can be set to give the desired rotation (with k_θ finite). This works for any object with angles between the sides that satisfy eqn. (6), if the sides are long enough to keep the fingers from slipping off the ends. (However, an object with non-parallel sides may eventually translate out of the grasp if it is rolled back and forth, because it will slide more in one direction).

Fig. 15 shows rolling a two dimensional part with both slip and rotation. In Fig. 15A, the object is stably grasped because the finger forces are within the friction cone. Since finger one is at the nominal angle θ_o, the tangential restoring force F_θ is zero. In Fig. 15B the nominal angle has been changed to cause rotation. This causes a restoring force (F_θ) that attempts to push the finger towards the nominal angle. The force at finger one is now outside the friction cone, so finger one will slip and the object will roll clockwise about the fixed finger, due to the moment $M_2 = F_\theta \mid \vec{r}_1 \mid$.

In Fig. 15C, the object's slip and rotation have reduced the angle error $\Delta\theta$ and thus F_θ. The surface normal at finger one is closer to F_r, so that the force is within the friction cone. At this point, slip stops at finger one, but rotation continues until F_θ is zero as in Fig. 15D. As finger one and the object move together, the main force is in the radial direction, keeping the object stably grasped.

9.0 DISCUSSION

A realistic finger will not have a negligibly small radius and a point contact. A soft finger with friction can exert a moment at a contact as well as forces. This torque due to the finger covering compliance will help stable grasping by exerting reaction torques to oppose disturbance moments. This can be exploited to improve marginal grasps.

Allowing slip in this grasping model prevents objects from being given an arbitrary rotational and translational stiffness. However, it seems that slip could be used to get some of the benefits of true compliance. For example, the damage done to a part colliding with a hard surface can be reduced by allowing the part to slip within the hand, without leaving the grasp.

The slip also means that without feedback from the hand, part orientation and position are not known. This may be adequate for simple part transfers, but assembly operations generally require higher precision, and for problems such as threading a bolt in a tapped hole, the orientation of the part can be critical. Extra fingers or tactile feedback can be used to reduce the orientation uncertainty.

In this paper, a simple way to look at grasping polygons was developed that is not very dependent on specific orientations and finger locations. If limited slip can be allowed, the object is likely to end up in a stable location by passive adaptation to the finger forces. This grasp may not be optimum, but it is feasible.

For a shape more complicated than a polygon, such as an ellipse, more precision will be necessary because the relations between the angle of force and object rotation and slip do not lead to stability. It is difficult to regrasp an ellipse with only three fingers because there are only two narrow locuses of grasp pairs available. So when this part is being manipulated, it is probably necessary to maintain three finger contacts at all times. This could be achieved by using four

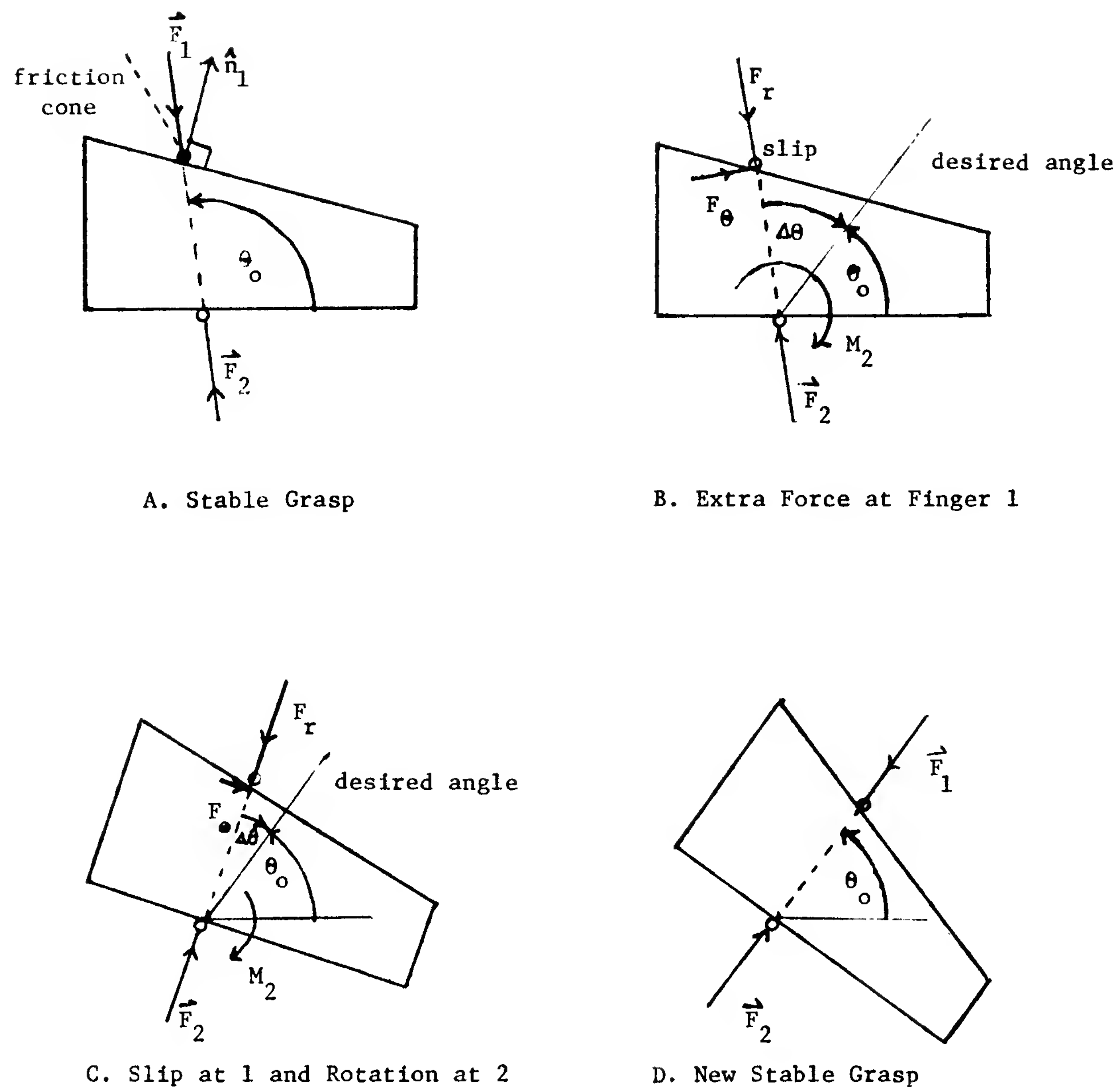


Figure 15. Part Rolling

fingers, or slipping the three fingers along the surface as they are moved to new locations.

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